# System for magnetic resonance imaging

The invention relates to a system for magnetic resonance imaging, comprising a substantially cylindrical cavity, wherein the cavity has an axis of symmetry in the direction of a z-axis, wherein a subject can be examined within the cavity, and wherein the subject has a conductance which is not isotropic in an xy-plane which is perpendicular to the z-axis.

The system can be an MRI apparatus or a radio frequency (RF) coil, wherein the latter can be used in NMR apparatus and in imaging systems based on NMR such as magnetic resonance imaging (MRI) or functional magnetic resonance imaging (fMRI).

For medical diagnosis images of tissue within the human body are often desired. For this purpose (nuclear) magnetic resonance imaging (MRI) has been used for roughly 30 years. This technology makes use of the fact that atoms, for example hydrogen atoms representing roughly 95 % of the human body, may have an odd number of nucleons. In this case the atom has a nuclear spin.

When the atom is exposed to an external magnetic field $\vec{B}_0$, the spin can be aligned either parallel or antiparallel to the magnetic field axis. These two possibilities to align the spins represent two energy levels of the formerly degenerated Kramer dublett. Due to the Boltzmann statistic the two energy levels have a different population such that the subject to be examined has a bulk magnetisation $\vec{M}$. $\vec{M}$ is parallel to the field $\vec{B}_0$.

If the subject to be examined is subjected to an additional magnetic field $\vec{B}_1$ which is not parallel to the field $\vec{B}_0$, then the magnetisation $\vec{M}$ is tilted out of the parallel configuration with $\vec{B}_0$. The magnetisation then precesses about the $\vec{B}_0$-axis with the Larmor frequency $\omega = \gamma B_0$. $\gamma$ is the gyromagnetic ratio which is characteristic for every atom. For hydrogen atoms the Larmor frequency is 128 MHz if the magnetic field strength is 3 T.

Applying a magnetic field $\vec{B}_1$ is normally done by coupling an RF wave into the subject to be examined, wherein the direction of the magnetic field vector $\vec{B}_1$ is perpendicular to $\vec{B}_0$, and wherein the frequency corresponds to the Larmor frequency of the

atom under consideration. For the purposes of this disclosure, a radio frequency is considered to include frequencies between about 1 MHz to about 100 GHz.

If the RF wave is coupled into the sample the magnetisation is tilted out of the parallel configuration with $\vec{B}_0$ as described above. Then a relaxation sets in such that the magnetisation $\vec{M}$ is parallel again to the magnetic field $\vec{B}_0$ after a certain relaxation time. Studying the relaxation times in detail makes it possible to derive a spatially resolved image of the subject to be examined. One possibility to do this is to perform a Fourier transformation of the time dependent spin-spin relaxation time.

In order to get an accurate image of the subject to be examined the bulk magnetisation $\vec{M}$ must have a well-defined angle $\alpha$ with respect to the rest-state magnetisation for all points in space after the application of the RF pulse. The rest-state magnetisation is parallel to $\vec{B}_0$. If, however, the RF field is spatially inhomogeneous, then a spectrum of angles $\alpha$ leads to a spectrum of spin-spin relaxation times. This however leads to an image with some intensity variations. As the intensity variations do not reflect variations in the properties of the tissue this may hamper the diagnosis. This is why an RF coil for NMR purposes must be designed to produce a spatially homogeneous magnetic field. Inhomogeneity may be caused by the design of the coil itself, or may be caused by the sample being positioned within the RF coil.

Numerous attempts are known in the prior art to improve the homogeneity of an RF coil. US 5,017,872 for example addresses the problem of inhomogeneity caused by the sample within the coil. The authors of this patent suggest to place a high permittivity material between the coil and the surrounding shield to reduce radial variations of the magnetic field of the cylindrical coil. This compensates for a contribution to inhomogeneity caused by the permittivity of the subject to be examined.

A similar approach is used by US 6,633,161 B1 which discloses an RF coil for an imaging system. The coil has a dielectric filled cavity formed by a surrounding conducting enclosure. In addition, a head of a patient to be examined may be positioned on a dielectric pillow to manipulate the RF magnetic flux in the region of interest in the patients head.

Increasing the magnetic field strength helps to achieve an increased signal-to-noise ratio and to increase the spatial resolution. In systems with magnetic fields of at least 3 tesla and with body sizes of 30 cm or more, the wavelength of the RF-field is roughly of the

same order as the size of the human body, or even smaller. This leads to an inhomogeneous $\vec{B}_1$-field because of eddy currents induced in the human body by the RF field, and because of dielectric reflections and the like. This inhomogeneity is much higher than in the case of lower field strengths.

It is an object of the invention to provide a system for magnetic resonance imaging of the kind mentioned in the opening paragraph with an improved homogeneity for high field strengths, particularly for field strengths at or above 3 tesla.

In order to achieve said object a system for magnetic resonance imaging in accordance with the invention is characterized in that an electrically conductive material is placed within the cavity, wherein the material has a conductivity and a thickness which render the total conductance in the xy-plane within the cavity to be isotropic.

The invention rests on the idea that an additional contribution to the inhomogeneity of an RF field arises because the subject within the cavity renders the electric conductance within the cavity to be anisotopic.

In the following the description will only refer to the case in which a person or an animal and thus a “subject” is examined in the cavity. The invention however is not restricted to this case, as the man skilled in the art will easily understand that it is also possible to examine “objects” in the cavity such as plants or other non-living material.

If a cylindrical cavity is chosen which has an axis of symmetry which is defined to be the z-axis, the conductance within the cavity in a plane perpendicular to the above-mentioned z-axis is not isotopic due to the subject to be examined. This is the case because the subject is non-cylindrical and has a conductivity $\sigma \neq 0$.

The above-mentioned plane perpendicular to the z-axis will be called the xy-plane. The x-axis, the y-axis and the z-axis represent a three-dimensional coordinate system with axes which are mutually orthogonal to each other.

The electric conductivity $\sigma$ of the subject to be examined is responsible for an attenuation of the RF field. On a microscopic scale the RF wave is described by a damped amplitude which leads to a limited penetration of the wave into the subject. The degree of attenuation however is not spatially uniform within the cavity when the subject to be examined is positioned within the cavity. The underlying reason is the spatial extension of the subject to be examined.

If a patient is positioned within the cavity, he normally lies on a substantially plane surface of a patients bed. The normal to the patients bed is chosen to be the y-axis. The body of a patient has a larger extension in the direction of the x-axis than in the direction of the y-axis. The x-axis lies in the substantially plane surface representing the patient's bed, as can be derived from the explanations above. This often leads to an attenuation of the RF field which is larger in the x-direction than in the y-direction.

In order to compensate for this effect an electrically conductive material is placed within the cavity, wherein the material has a conductivity and a thickness which render the total conductance in the xy-plane within the cavity to be isotropic. The total electric conductance comprises the conductance of the patient and the conductance of the material.

The additional material has a thickness and an electric conductivity which is chosen to have such a value that the total electric conductance for all radial directions is the same within the xy-plane. This leads to a planar isotropy of the electric conductance in the xy-plane, which in turn reduces the inhomogeneity of the RF field.

As can be derived from the explanations above the system for magnetic resonance imaging might be an MRI apparatus or a radio frequency coil for magnetic resonance imaging.

A couple of possibilities exist to position the material within the cavity. Investing in additional holding devices within the cavity is one possibility. It is however easier if at least a part of the material is attached to an inner wall of the cylindrical cavity. When referring to the circular plane of section of the cavity with the xy-plane, the material can be fastened to a segment of the inner wall.

In addition at least a part of the material can be attached to a bottom of a substantially plane surface (the patients bed) on which the subject can be positioned. The material may then be an integral part of the patients bed.

For medical diagnosis it is not always the whole body of the patient which needs to be examined, but it may only be the abdomen, the spine, or the patients head. As the geometry of the region of interest is different in these cases, a more flexible compensation as mentioned above is possible if the electrically conductive material is removably attached within the cavity, for example to the inner wall of the cavity or to the patients bed as described above. In this case the dimensions and/or the conductivity of the material in the x-direction and in the y-direction can be adapted to the circumstances.

For practical reasons the material is only placed substantially above and below the subject to be examined, as this is sufficient in the case of a patient lying on the patients bed. In this case the patient is aligned parallel to the z-axis, and the extension of his body within the xy-plane is not circular. Although the extension of a very well nourished person within this xy-plane might approximately be circular, most people could be modelled as an ellipse fitting within the aforementioned circle. A region exists between a body in the form of the cylinder and a body having such an extension in the xy-plane. Inhomogeneity arises because this region, which is not symmetric with respect to the z-axis, is not filled with human tissue. The material being placed in the cavity thus has the function to compensate for this region of missing conductance to ensure that the conductance within the xy-plane is isotropic.

From the above explanations it can be seen that the region of missing conductance are two sickle-shaped regions facing the back and chest of the person. In the simplest case the electrically conductive material is placed only above and below the patient to compensate for these two sickle-shaped regions. Placing electrically conductive material to the left and to the right of the patient lying on the patients bed is in most cases not necessary.

Another possibility to position the material in the cavity is to place the material on top of and/or beneath the patient. This can be done by choosing a material being shaped as a sheet. At least a part of the patient's body can be covered by such a sheet which is used like a blanket.

Experiments have shown that a good compensation can be achieved with a material having a planar resistance between about 5 Ω and about 20 Ω.

It is preferred that the material above the subject to be examined has a lower planar resistance than the material below the subject. This is advantageous when the whole body of a patient needs to be examined, as for reasons of anatomy the compensation in the y-direction must be different from the compensation in the (-y)-direction.

Experiments have shown that a good compensation can be achieved with a material above the subject having a planar resistance between about 5 Ω . and about 1Ω, and a material below the subject which has a planar resistance of between about 12 Ω and about 16 Ω.

Numerous materials known in the prior art can be chosen for the above-mentioned compensation. The material can be a sheet which is at least partially covered by a conductive layer, for example a carbon-coated sheet of plastic. Such a sheet or foil can be attached to the inner bore of the cavity and/or the patients bed.

Furthermore it is possible that the above-mentioned material, for example a sheet, is not part of the MRI apparatus or the coil, but is a part separate and distinct from it. The patient may then lie on such an auxiliary material and/or he is partly covered by additional material. In the case of a sheet of electrically conductive material this auxiliary sheet can be used similar to a blanket. In this case the electrically conducting material can be used for improving the homogeneity of the RF field in the MRI system. This use is particularly helpful in cases in which the apparatus is designed to operate at magnetic fields of at least 3 tesla.

While it is generally desired to have a homogeneous RF field within the cavity, deliberate inhomogeneity may be an option in particular circumstances. In such a case a patterned material can be used which has local variations of its electric conductivity. As an example a sheet can be chosen of which only predetermined parts of its surface are covered by a conductive layer. Such a pattern can for example be achieved by a chemical vapour deposition process.

Embodiments of a system for magnetic resonance imaging in accordance with the invention are described in detail in the following with reference to the drawings, in which

Fig. 1 shows a top side view of an RF coil according to the invention;

Fig. 2 shows the interior of the RF coil of Fig. 1 when seen in the z-direction; and

Fig. 3 shows an MRI apparatus in accordance with the invention.

Figure 1 shows a cylindrical birdcage coil 1 in accordance with the invention having its axis of symmetry along the z-direction. The opening of the coil 1 forms the xy-plane which is perpendicular to the z-axis. The interior of the coil 1 defines the cavity 2.

This coil 1 is equipped with an electrically conducting material 4 fastened to the inner wall 5. The plane of section between the xy-plane and the coil is a circle, the inner boundary of which is partially covered by the material 4. The material 4 forms an upper and a lower segment.

Figure 2 shows the coil 1 of Figure 1 when looking in the z-direction. Coil 1 has a substantially plane surface 7 as the upper surface of the patients bed. The patient 3 is shown in a highly simplified way as an oval body, as the shape of a human body within the

xy-plane can be approximated in this way. The electrically conducting material 4 is attached to the inner wall 5 of coil 1, as well as below the bottom 6 the patients bed.

The patient 3 is covered by a plastic sheet 8 which has a carbon coating (not shown). In experiments with a saline phantom, which mimicks size, aspect ratio and conductivity of a human body, good results were obtained when the sheet 8 had a planar resistance of 8 Ω when placed at the top of the patient 3, and about 12 Ω to 16 Ω when placed at the bottom of the phantom. The sheets had a length of 70 cm in the form of an alternating sequence of 5 cm and 10 cm wide strips with a gap between them. The sheet at the bottom was the same with the difference, that the gaps between the strips were very narrow.

Figure 3 shows an MRI apparatus 10 in accordance with the invention being equipped with a coil 1. The apparatus 10 has a bed with a surface 7 on which the patient lies. The figure shows an application in which only the head of the patient is examined, for example to enable the diagnosis of a tumour in the patients head.

Particularly spine-imaging may suffer from inhomogeneities of the $\vec{B}_1$-field. The underlying reason is that the spine may exactly coincide with black spot found in MRI images which stem from regions with inhomogeneous radio frequency field. For such application it may be advantageous to place an electrically conducting sheet in an asymmetric fashion. Experiments with two sheets having a planar resistance of 9 Ω being 10 cm wide, and being placed beneath the phantom proved to be successful. The hotspots were lowered at the expense of the reduced intensity elsewhere.